Two-dimensional electron density and temperature profiles of EUV light sources with 4.0% CE

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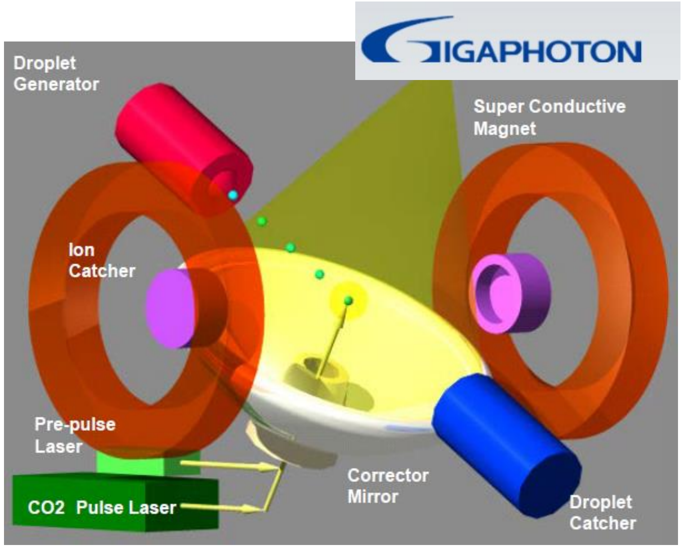
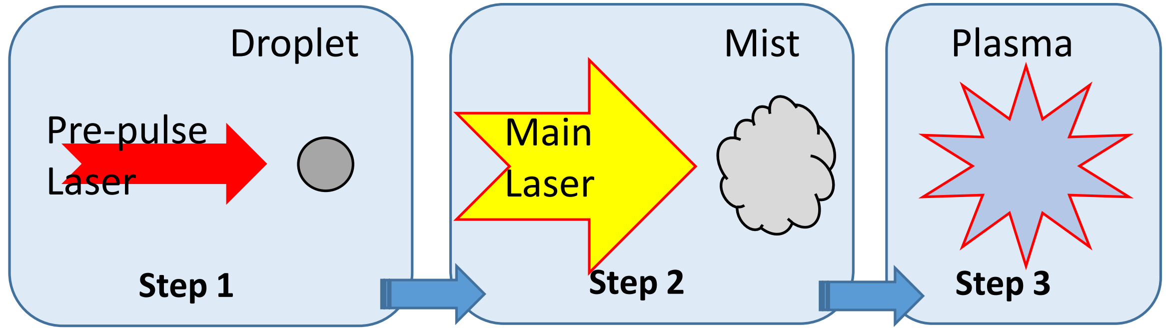
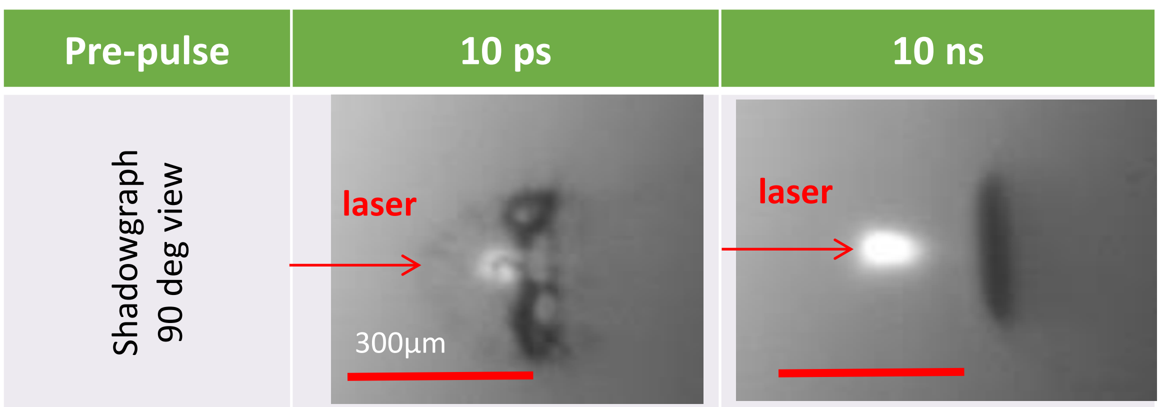
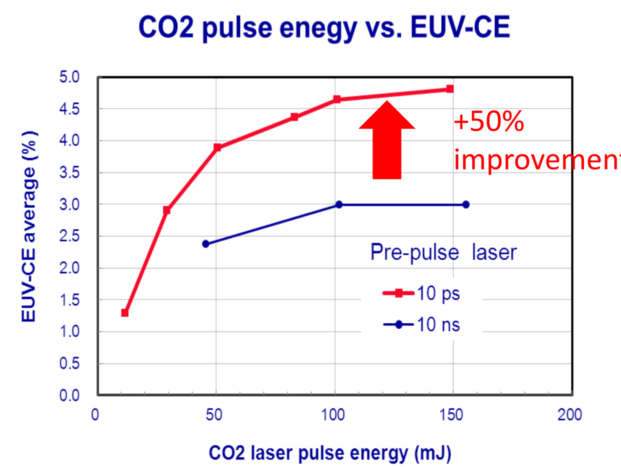
Motivation



Droplet Sn + Double pulse laser







↗ conversion efficiency (CE)

↗ output power

Structure? Limitation ? Improvement ?

Diagnostic method

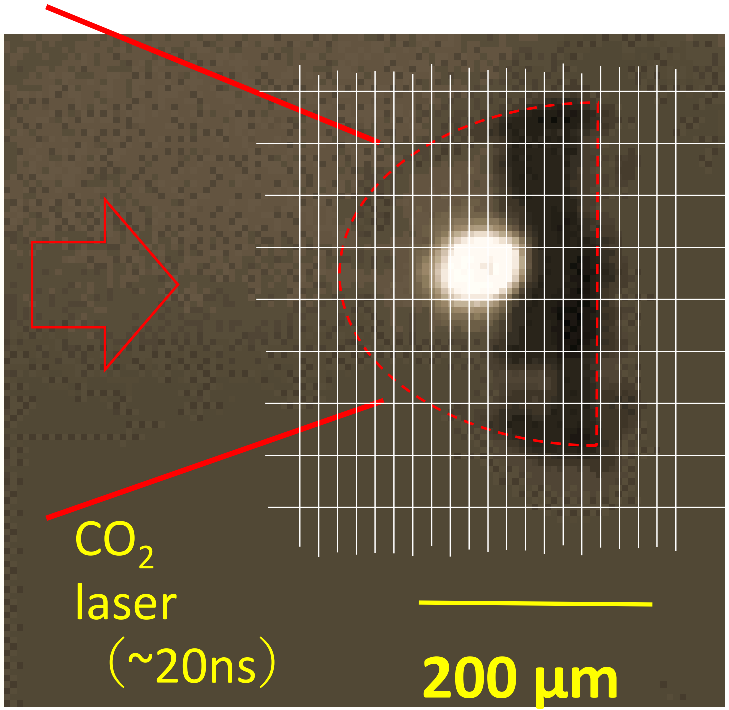
We have revealed the structure of EUV light source plasmas by using the world's best spatial resolution measurements.

Collective Thomson scattering

- Spatial resolution （~20 μm）
- More than 200 points
- Electron density(n_e), temperature(T_e)

further information

Yuta Sato's poster



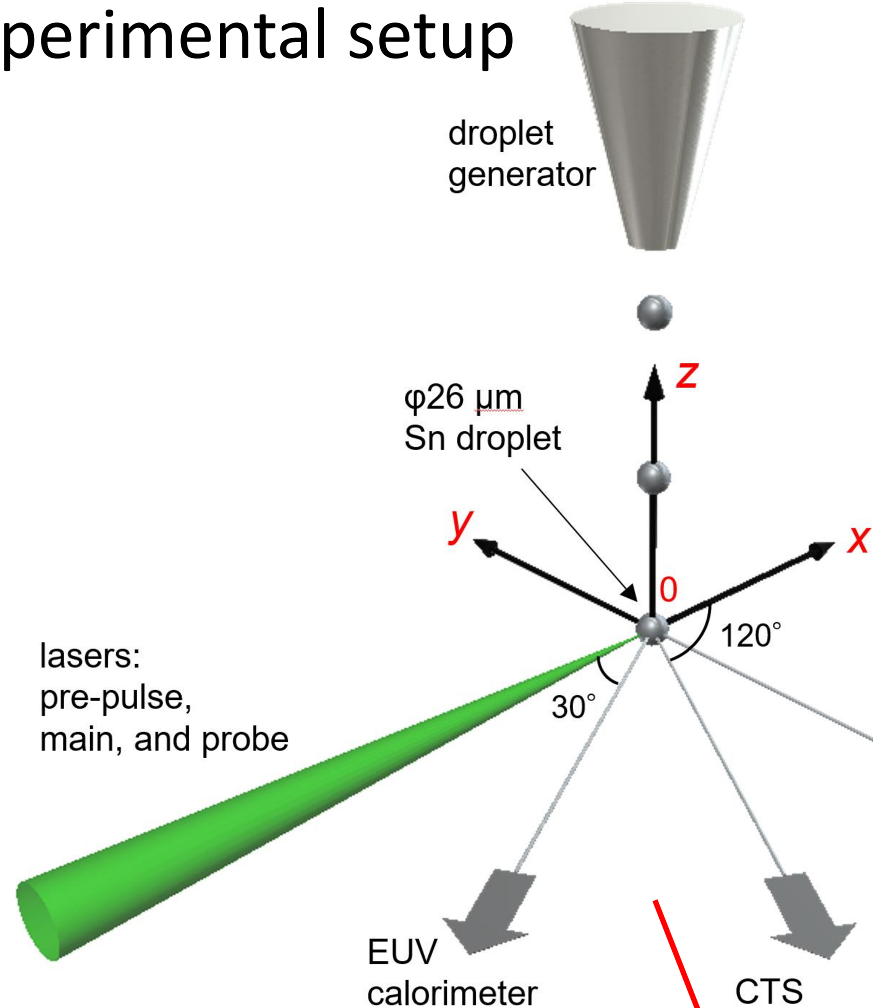
Shadow of expanded Sn target

Highlights

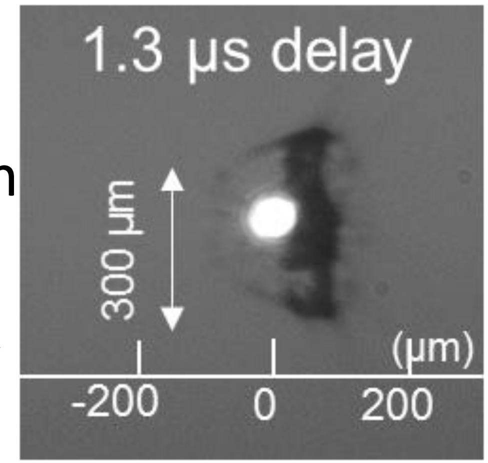
- We can clearly explain why the CEs were changed using the 2D-plasma parameters.
- It is possible to explain the CE values using the plasma parameters and atomic model.
- Monitoring of the 2D-plasma parameters can be a powerful tool for further improvement.

Experimental setup

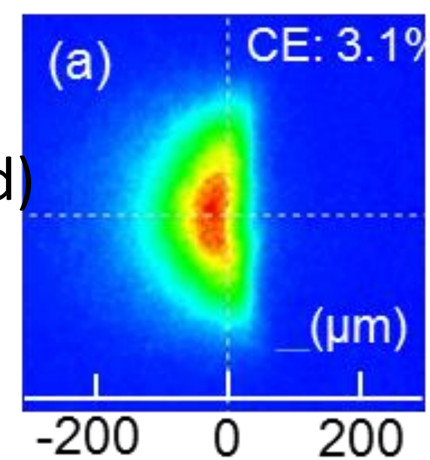
K.Tomita+ Sci. Rep.(2017)

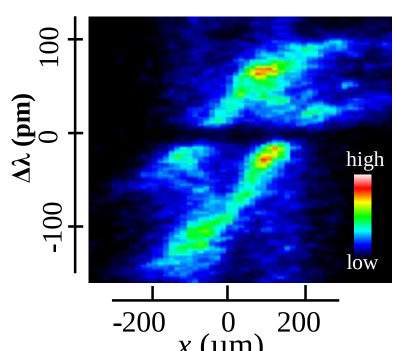


Shadowgraph



EUV image
(line-integrated)





Thomson
scattering

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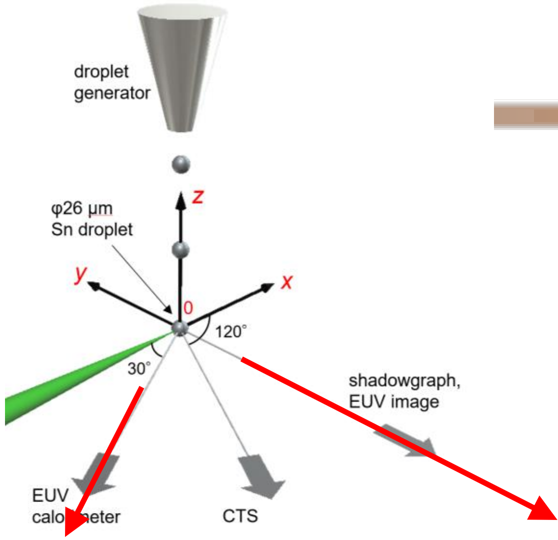
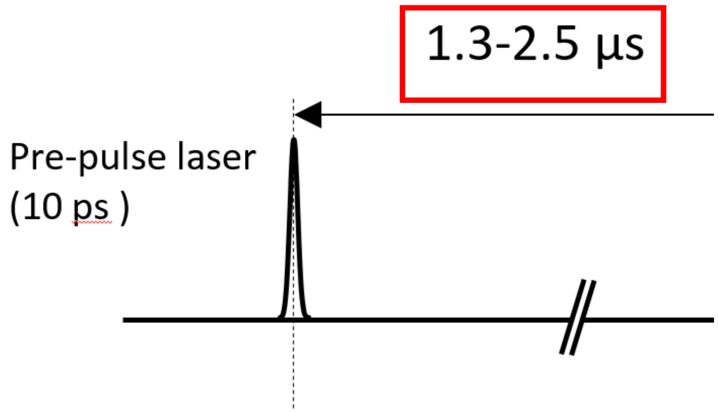
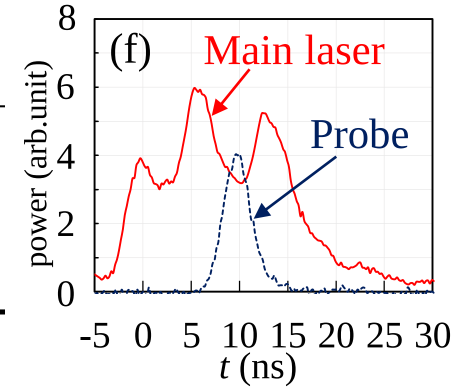
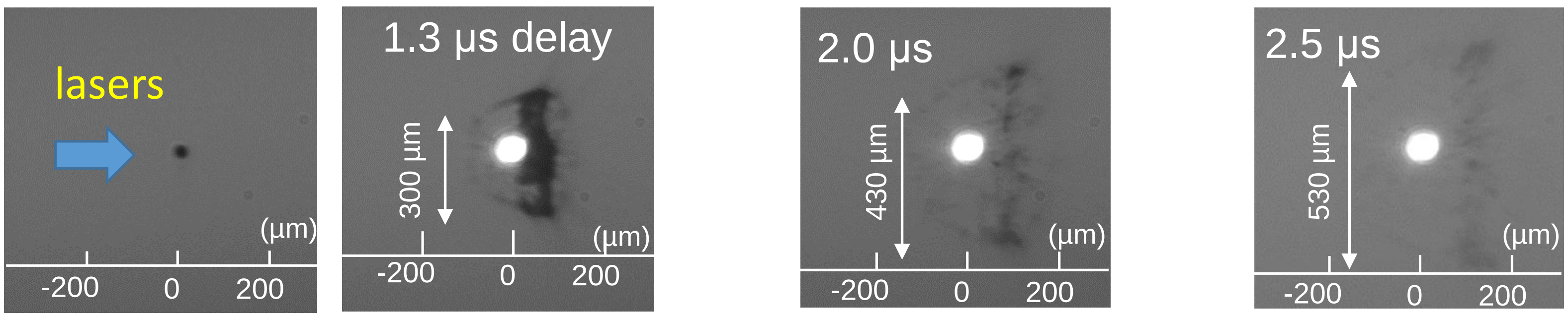
Plasma production scheme



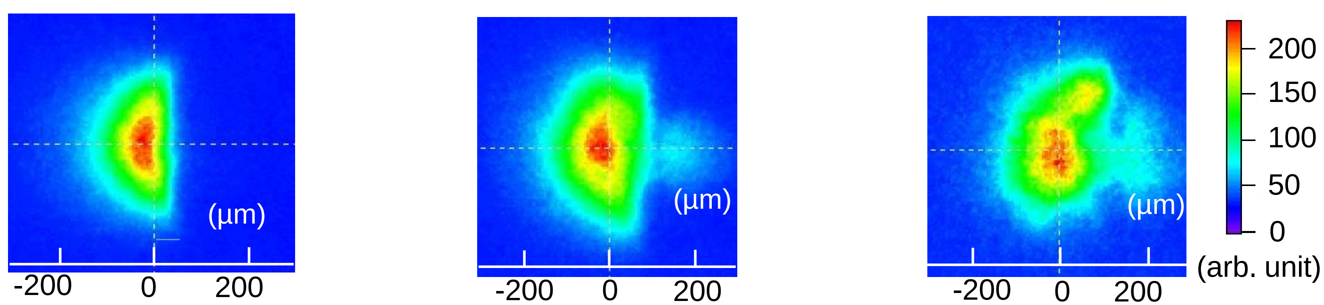




shadowgraph



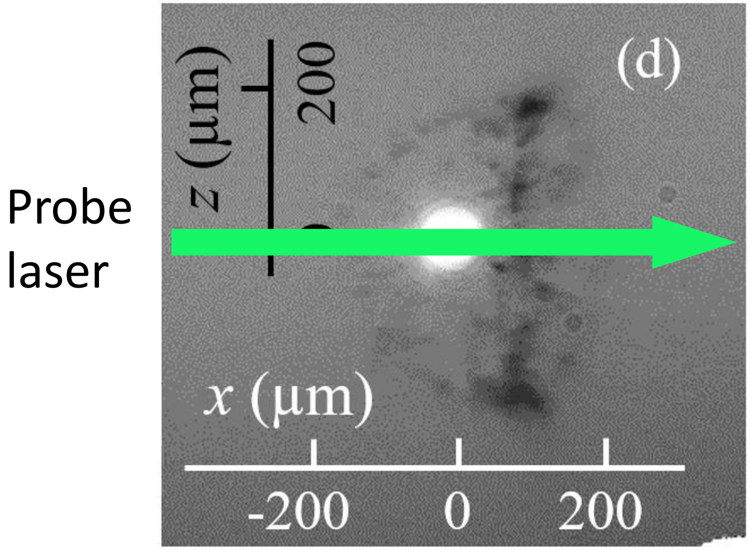
EUV image

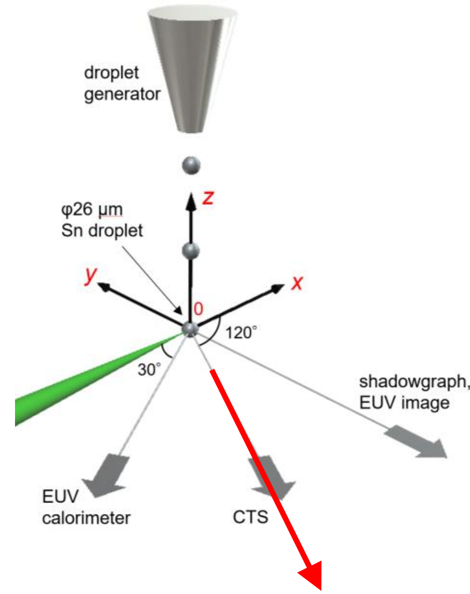


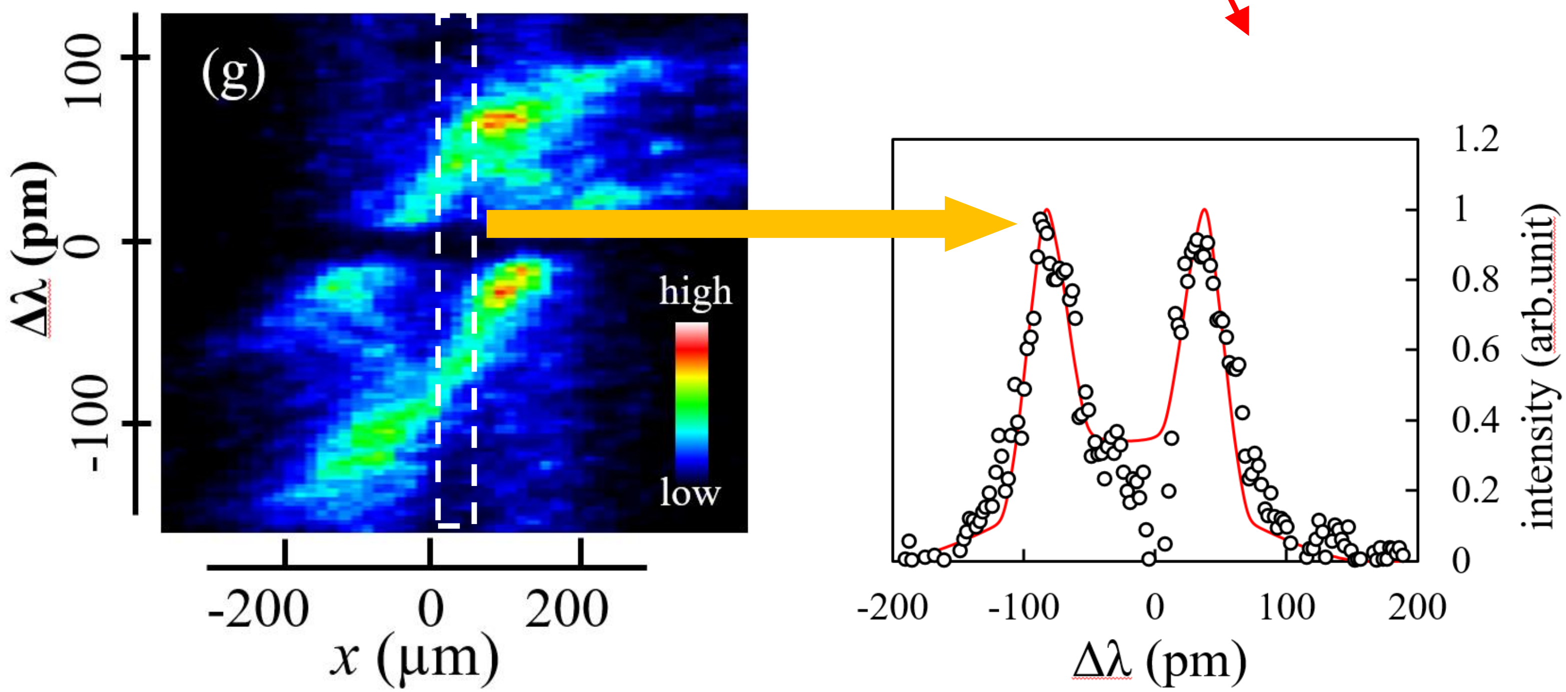
CE 3.1 % 4.0 % 2.8 %

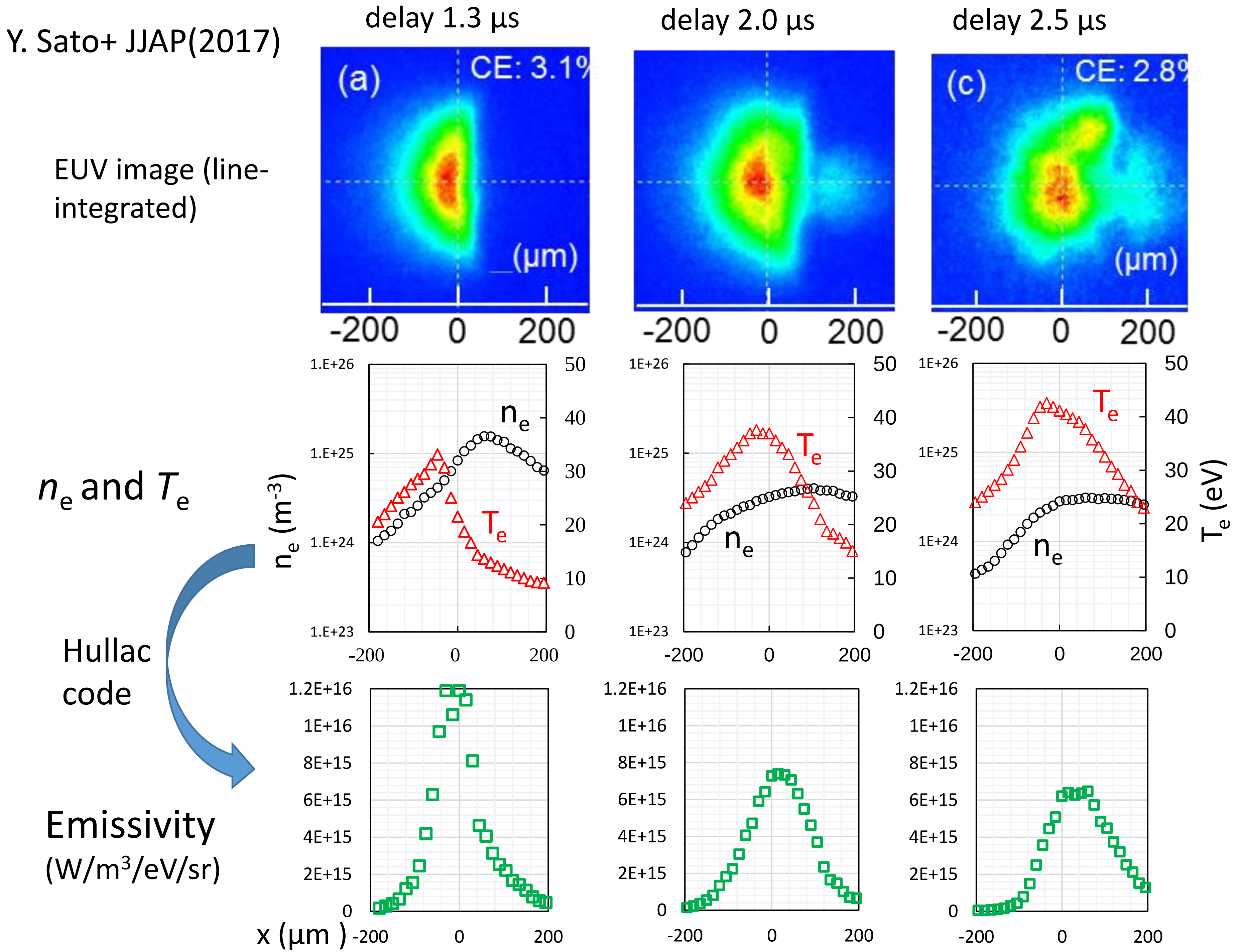
delay 2.0 μs

K.Tomita+ Sci. Rep.(2017)



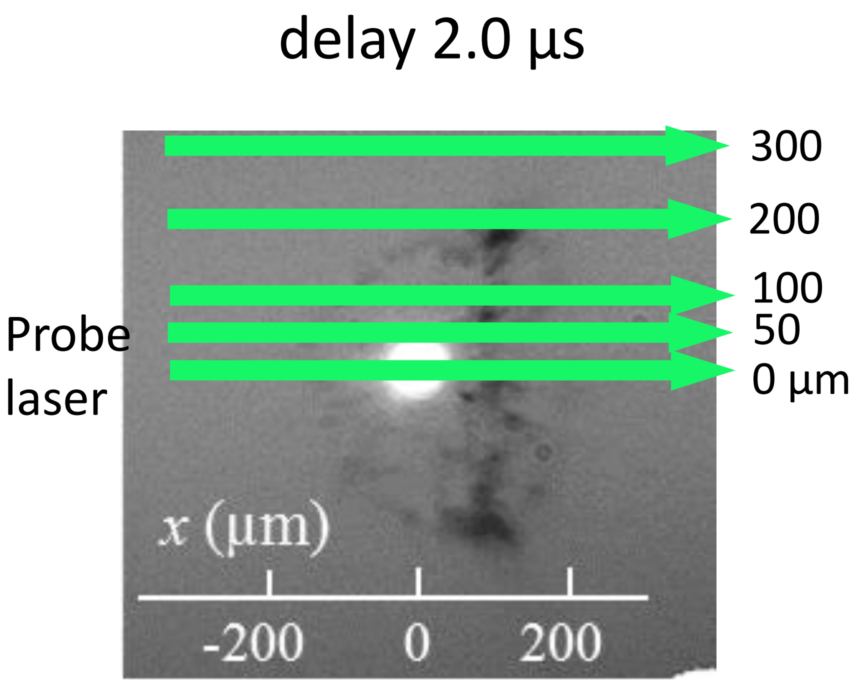


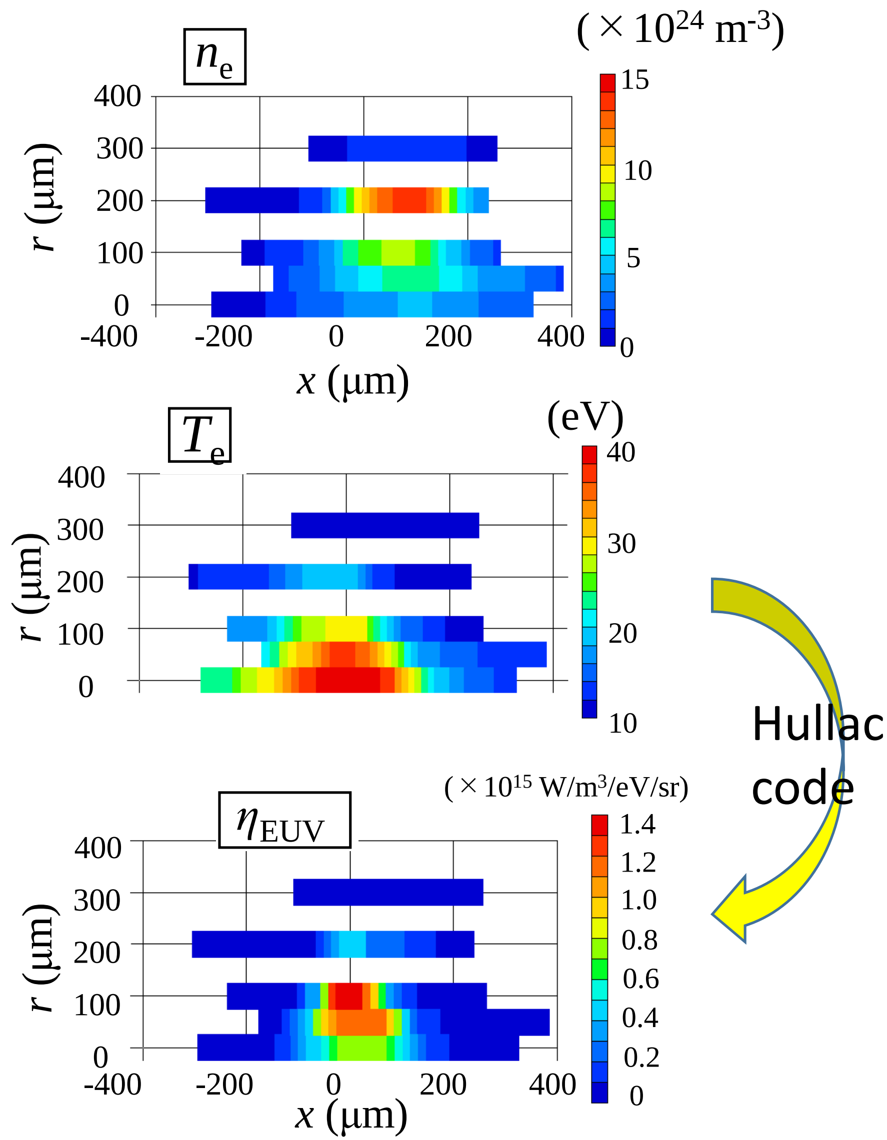




Y. Sato+ JJAP(2017)
delay 1.3 μs
delay 2.0 μs
delay 2.5 μs
EUV image (line-integrated)
(a)
CE: 3.1%
(μm)
(c)
CE: 2.8%
-200
0
200
n_e and T_e
n_e (m^{-3})
T_e (eV)
n_e
T_e
1.E+26
1.E+25
1.E+24
1.E+23
1E+26
1E+25
1E+24
1E+23
50
40
30
20
10
0
Hullac code
Emissivity
($W/m^3/eV/sr$)
1.2E+16
1E+16
8E+15
6E+15
4E+15
2E+15
0
x (μm)

2D profiles of EUV source

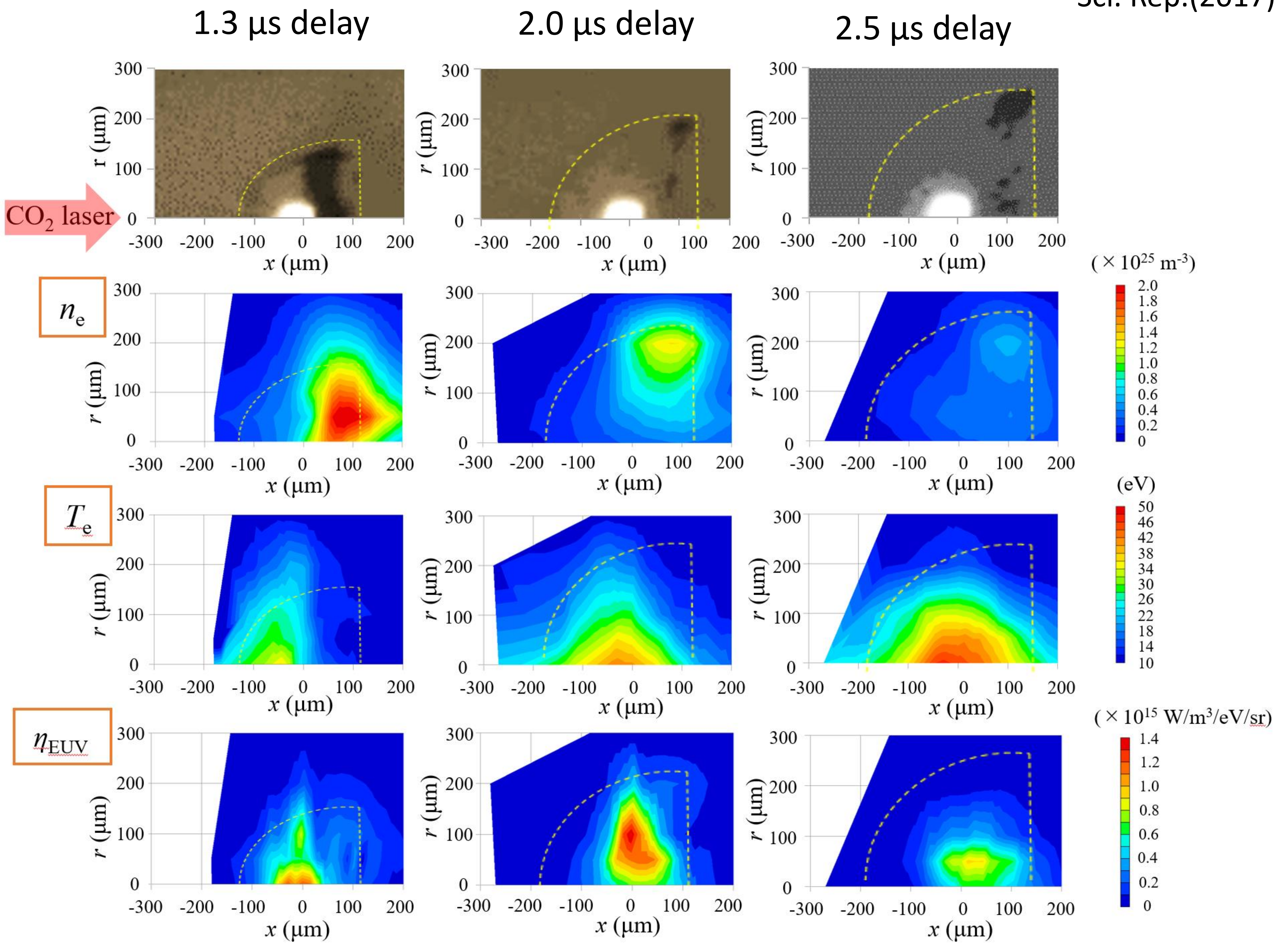




ne: Hollow-like profile

Te peak : center axis(r=0)

Emissivity peak: not on r=0

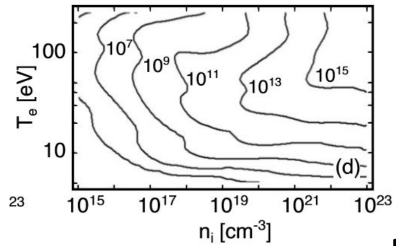

1.3 μs delay
2.0 μs delay
2.5 μs delay
CO2 laser
n_e
T_e
η_{EUV}
r (μm)
x (μm)
(×10^25 m^-3)
(eV)
(×10^15 W/m^3/eV/sr)

Discussion1

Sci. Rep.(2017)

A. Sasaki et al., J. Appl. Phys. (2010)

Atomic modeling

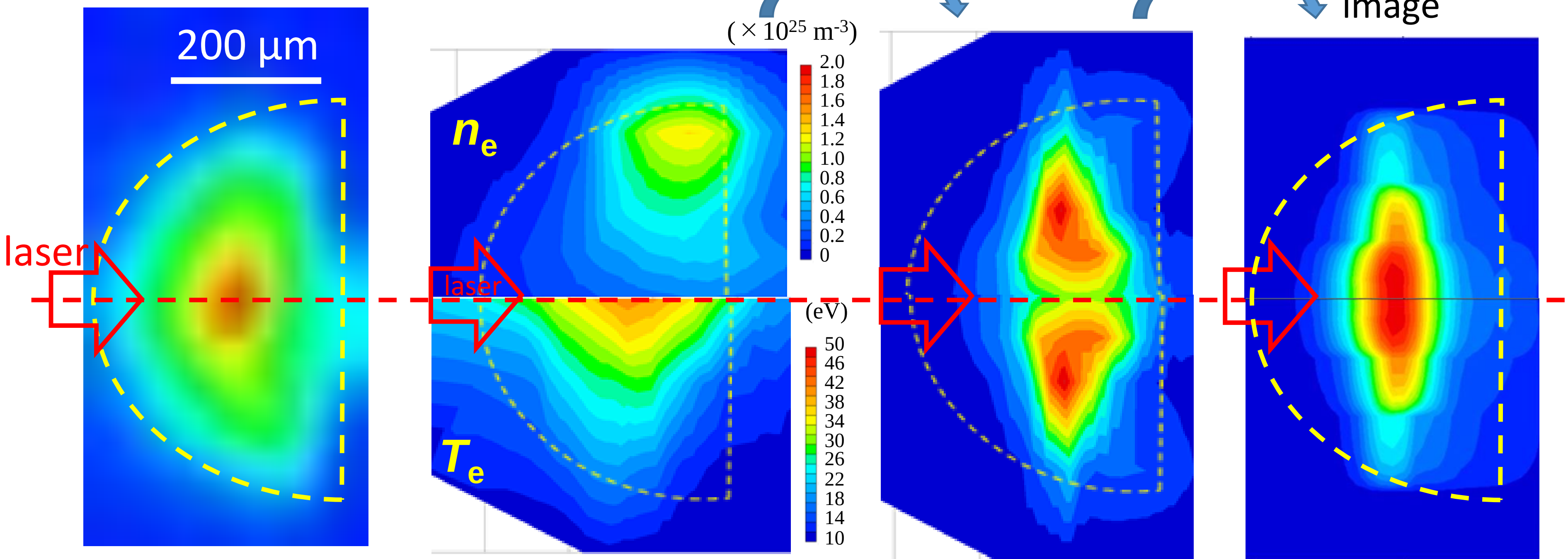


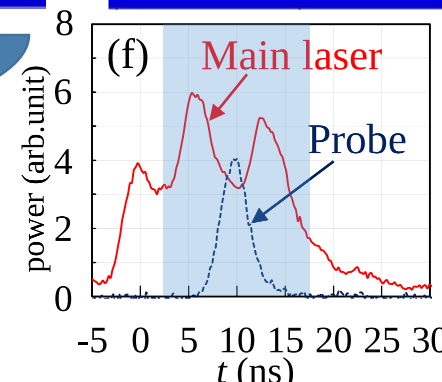
EUV image

n_e, T_e

Emissivity

reconstructed image



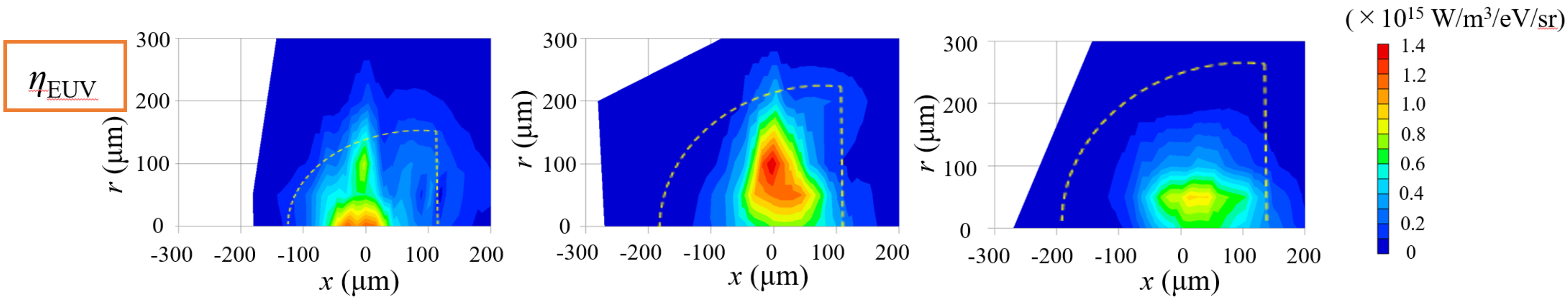


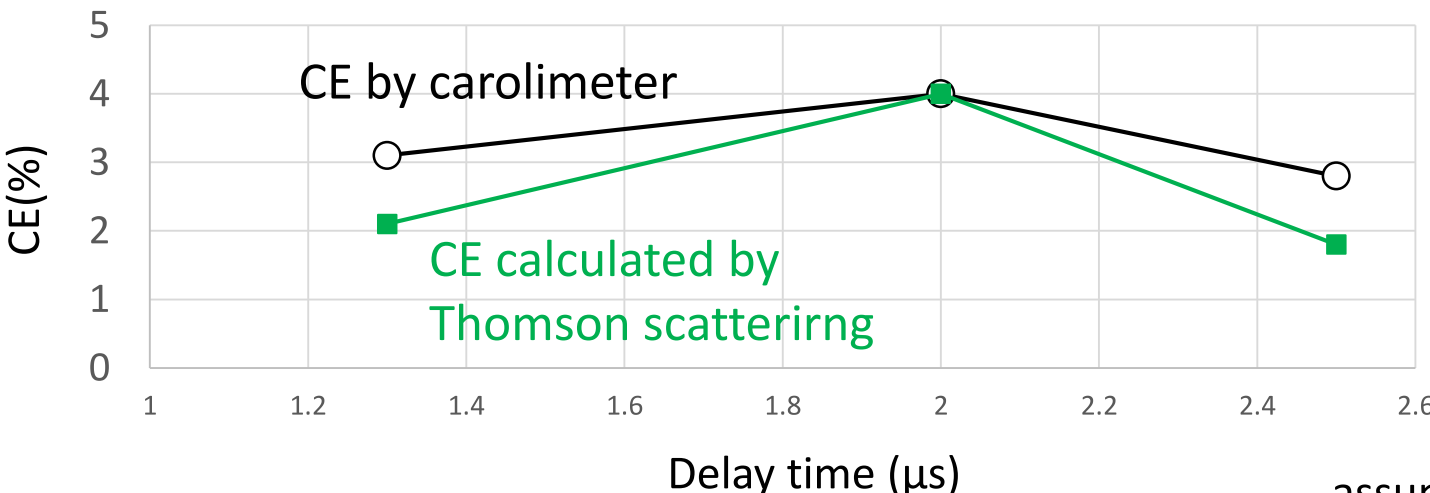
Results of line-integrated, self-absorbed

Discussion2

Sci. Rep.(2017)

1.3 μs delay　　2.0 μs delay　　2.5 μs delay





assumptions:
axial symmetry
isotropic distribution
EUV duration 20ns

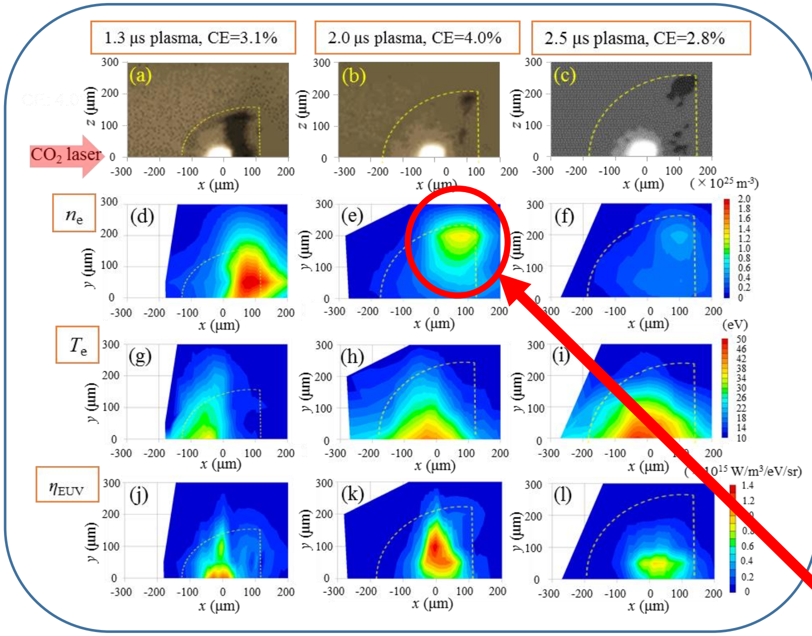
Conclusions

For the first time, we have revealed the detailed structure of EUV light source plasmas by the world's best spatial resolution Thomson scattering measurements.

Results clearly show that intense EUV were obtained where the plasma conditions are adequate, which are predicted by atomic modelling studies.

The 2D profile of the inband EUV emissivity (ηEUV) was theoretically calculated using the CTS results and atomic model (Hullac ode), which reproduced a directly measured EUV image reasonably well.

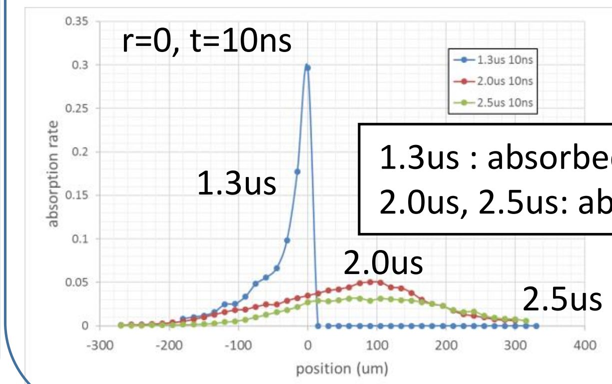
Future work: How can we improve the light source?



laser absorption (inverse bremsstrahlung) is proportional to ne, $Te^{-3/2}$

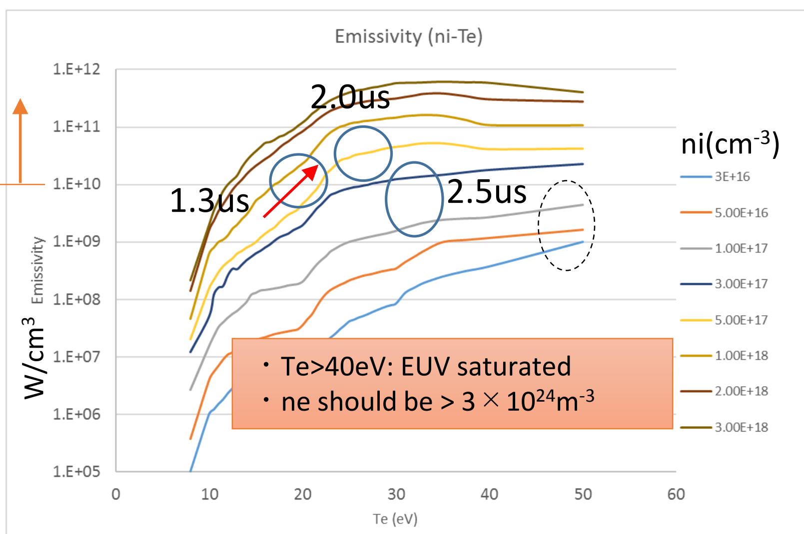
$$k_{abs}^{las} = \frac{16\pi Z n_e^2 e^6 \ln\Lambda(\nu)}{3c\nu^2 (2\pi m_e k_B T_e)^{3/2} \left(1-\nu_p^2/\nu^2\right)^{1/2}}$$

(Dawson)



1.3us : absorbed in narrow width
2.0us, 2.5us: absorbed in wide width

emissivity, ne, and Te (Sasaki+JAP2010)

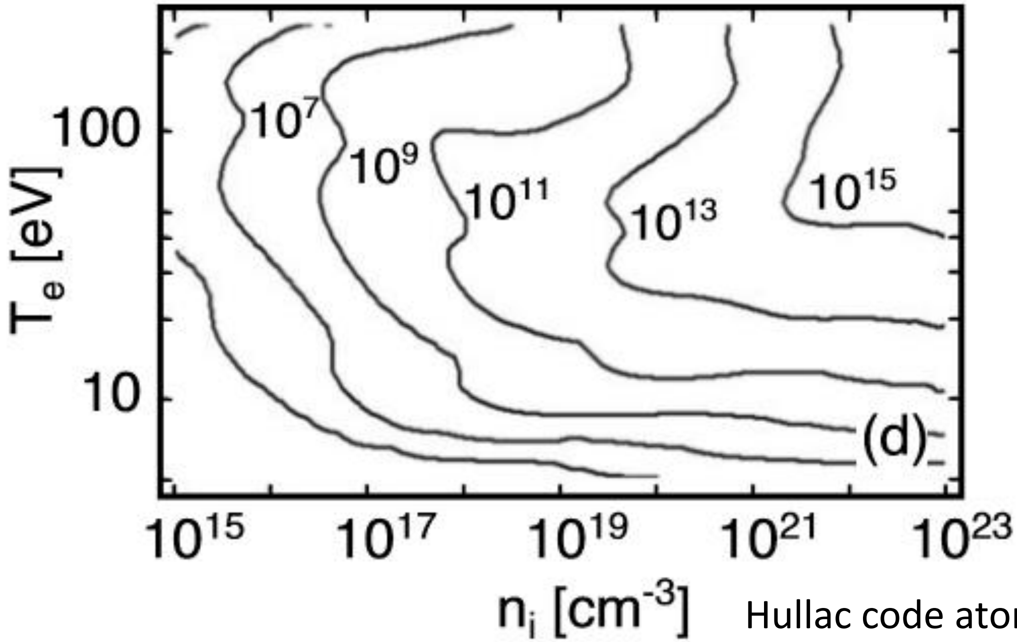


Even for the highest CE condition, there are many low temperature(<15eV) Sn ions within the etendue limit!

Atomic modeling

Strong correlation between (T_e, n_e) and EUV emissivity

EUV emissivity(W/cm^3) contour diagram



Hullac code atomic modeling
A. Sasaki+ JAP(2010)

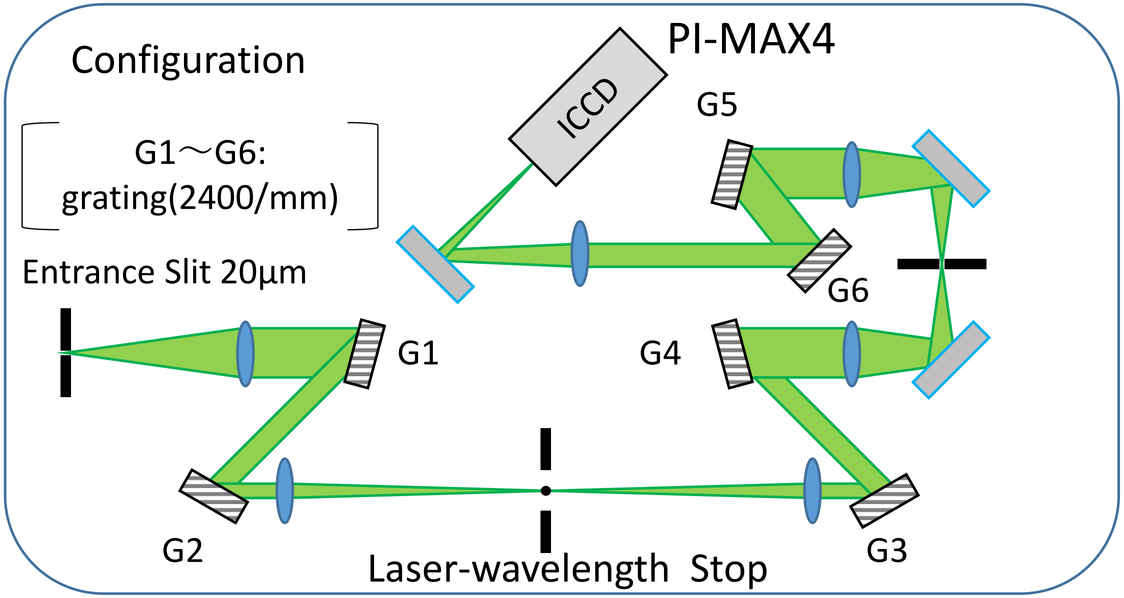
Optimum:
$n_e = 10^{24} - 10^{25}$ m^{-3}
$T_e \sim 30 - 50$ eV
$Z \sim 10$

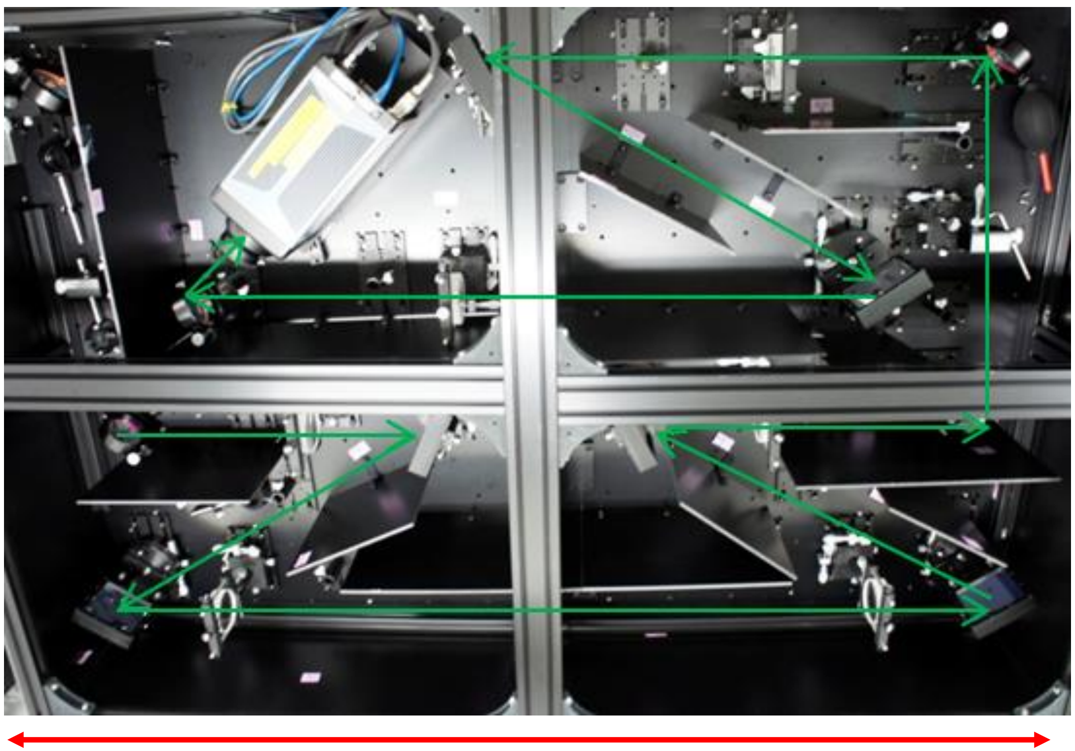
*non-linear dependence

e.g., 10eV, 30eV

10^2 EUV

Plasma diagnostics are essential





2m

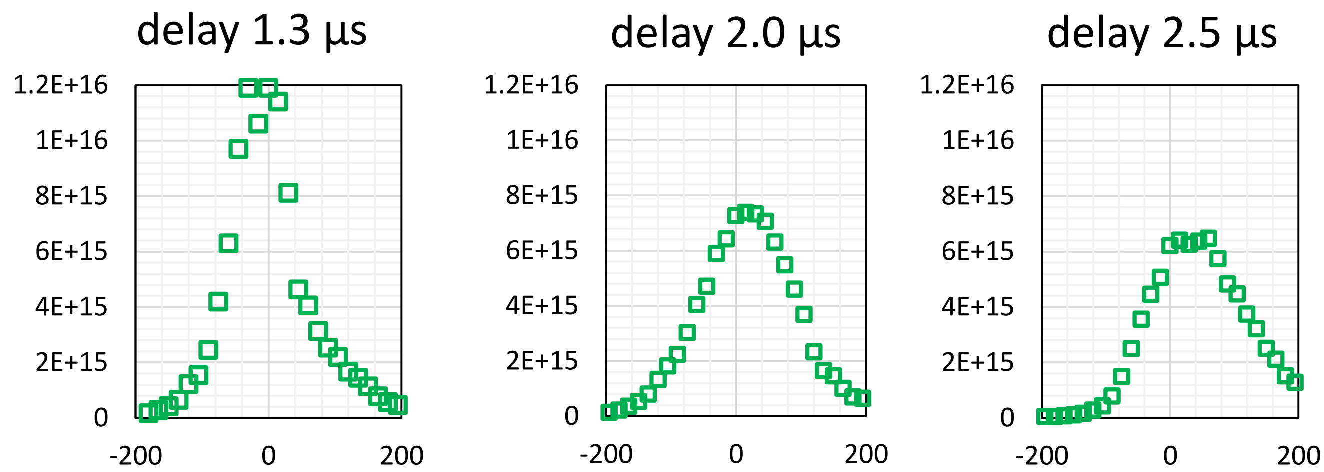
K. Tomita+, APEX(2015)
Y. Sato+, JJAP(2017)

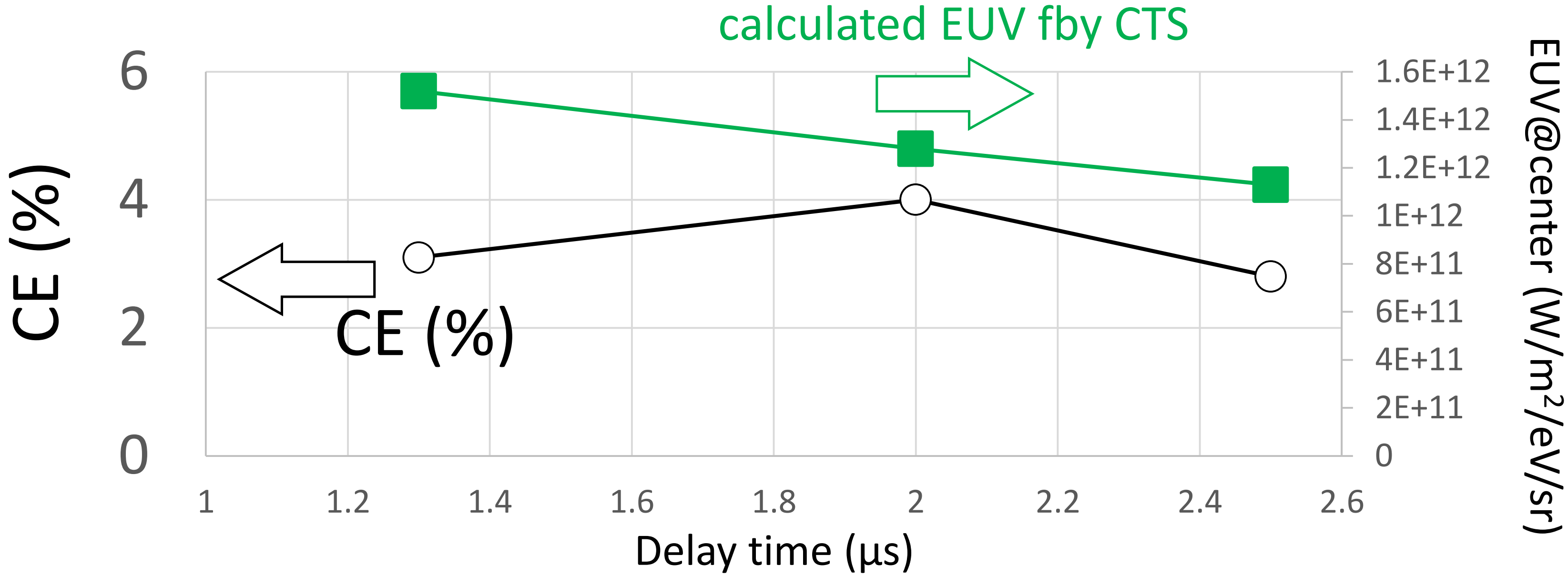
spectrometer for CTS

- spectral resolution （10pm）
- stray light rejection(±14pm)(± 0.5cm^{-1})

a few tens of improvement from conventional system

Emissivity calculated by CTS and atomic modeling ($W/m^3/eV/sr$)





CE peak：delay 2.0 µs.

However, EUV peak @center axis : delay 1.3 µs